Vardanega, P. J., Haigh, S. K., & O'Kelly, B. (2021). Use of fall-cone flow index for soil classification: a new plasticity chart. *Géotechnique*. https://doi.org/10.1680/jgeot.20.P.132

Use of fall-cone flow index for soil classification: a new plasticity chart

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Use of the Casagrande-style plasticity chart to classify fine-grained soils using Atterberg's liquid and plastic limits is ubiquitous in geotechnical engineering. This classification is dependent on the thread-rolling and Casagrande-cup tests, which are both more operator dependent than the fall-cone liquid limit test. This paper shows that the slope of the data acquired during the fall-cone liquid limit test (the fall-cone flow index) can be used to redraw the plasticity chart, thus allowing classification of fine-grained soils to be achieved solely from fall-cone liquid limit data.

KEYWORDS: laboratory tests; soil classification; standards & codes of practice; statistical analysis

INTRODUCTION

Soil classification charts

The Casagrande plasticity chart (Casagrande, 1947) is one of the most recognisable tools in geotechnical engineering. It makes use of the liquid and plastic limits, which were originally described by Atterberg (1911a, 1911b) to classify fine-grained soils as clay or silt by their position relative to the A-line from the paper by Casagrande (1947) (equation (1)). The A-line was originally an empirical line dividing silts and clays (including organic materials) (Casagrande, 1947) but has since become the de facto classification tool for clays and silts, with particle size distribution (in theory the definitive method) being almost completely replaced. The U-line (equation given in the paper by Howard (1984) and shown in this paper as equation (2)) '… was recommended by Casagrand[e] as an empirical boundary for natural soils. It provides a check against erroneous data, and any test results that plot above or to the left of it should be verified' (Howard, 1984: p. 221).

$$I_{\mathrm{P}}(\%) = 0{\cdot}73\,[w_{\mathrm{L}}(\%) - 20] \tag{1}$$

$$I_{\mathrm{P}}(\%) = 0{\cdot}9\,[w_{\mathrm{L}}(\%) - 8] \tag{2}$$

where I_{P} is the plasticity index and w_{L} (%) is the liquid limit.

Polidori (2003, 2004, 2007) proposed a revised classification chart to separate fine-grained soils into clays, silts and organic soils by making explicit use of the clay fraction in the classification system (although the clay fraction is not always reported in geotechnical studies and does require additional experimental work). Despite these recent proposed amendments, the Casagrande soil-classification framework is now almost universal, although differences exist in the method for liquid limit determination (e.g. BSI, 1990, 2018a; ASTM, 2017). The different liquid limit test methods (i.e. fall cone as recommended in BSI (1990) and the percussion-cup method as recommended in ASTM (2017)) can cause substantial variations in values of both liquid limit and I_{P}, as discussed by Haigh (2012, 2016), and hence for the classification of soils which lie close to boundaries. This can have substantial implications, for instance, when design codes are prescriptive about allowable soil classes but methods for testing Atterberg limits change (e.g. Di Matteo *et al.*, 2016). More recently, Reznik (2017) described a non-linear variation of the A-line (reported to be based on over 7000 fall-cone tests (using a Soviet Union era fall cone) on fine-grained soils from the Odessa region).

Thread-rolling test

While there are differences in worldwide codes of practice for liquid limit determination, the plastic limit (w_{p}) is, to date, still most often determined by the thread-rolling test. Many publications have sought to achieve w_{P} determination using fall cones, generally by extrapolating fall-cone data (e.g. Feng, 2000) using the assumption of a 100-fold increase in soil undrained shear strength across the plastic range (i.e. from liquid to plastic limit) (e.g. Schofield & Wroth, 1968; Wroth & Wood, 1978). This approach is not reliable, rather it defines a different parameter, the plastic strength limit (Haigh *et al.*, 2013; Sivakumar *et al.*, 2016; O'Kelly *et al.*, 2018). Shimobe & Spagnoli (2019) presented a study comparing the plasticity index and liquid limit deduced using the 'extended fall-cone method' (as previously stated, such methods are often based on the inaccurate assumption of a 100-fold strength variation across the plastic range of water contents; c.f. Vardanega & Haigh (2014)) with the conventional Casagrande approaches. Shimobe & Spagnoli (2019) showed that extrapolated w_{P} values derived using an 'extended fall cone method' correlated well with thread-rolling values. Shimobe & Spagnoli (2020) recently made use of the 'extended fall cone method' to redraw the Casagrande classification chart.

Haigh *et al.* (2013) demonstrated that the undrained shear strength at the plastic limit is not a constant, but varies widely, and that the range of undrained strengths could be explained using critical state soil mechanics (Schofield & Wroth, 1968). The aim of this paper is to use the fall-cone flow index to develop a new soil classification chart that can be used to classify fine-grained soils with only fall-cone data.

FLOW INDEX

Sridharan *et al.* (1999) defined a flow index (denoted here as $\mathrm{FI_c}$ to avoid confusion with the flow index F from the

Manuscript received 27 April 2020; revised manuscript accepted 29 January 2021.
Discussion on this paper is welcomed by the editor.

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Casagrande cup) for fall-cone liquid limit (i.e. $w_{L\ FC}$) test data given by equation (3). The same concept was used for Casagrande-cup liquid limit (i.e. w_L) test data by Fang (1960) (and also in the recent work of Spagnoli *et al.* (2019)).

$$\mathrm{FI_c}(\%) = \frac{\partial w\,(\%)}{\partial \log_{10} d} \tag{3}$$

where d is the fall-cone penetration depth (mm).

Sridharan *et al.* (1999) showed for 41 soils from India that a high degree of correlation existed between the flow index (as determined using the BSI (1990) 30°, 80 g cone with $d = 20$ mm at the liquid limit) and plasticity index ($I_P = w_{L\ FC} - w_P$) such that

$$I_P(\%) = 0{\cdot}75\mathrm{FI_c}(\%) \quad r = 0{\cdot}99,\ n = 41 \tag{4}$$

USE OF FALL-CONE DATA TO CLASSIFY SOILS

Vardanega & Haigh (2014) assembled a large database of fall-cone tests on 101 fine-grained soils. This database was re-analysed along with the stated $\mathrm{FI_c}$ data from Sridharan *et al.* (1999), fall-cone data digitised from Campbell (1975) and Sampson & Netterberg (1985), Vardanega *et al.* (2019) and data from the Trinity College Dublin (TCD) soils database (see Table 1) to test equation (4) on a larger dataset. As the original classification system developed by Casagrande (1947) included organic soils (see Fig. 5 from Casagrande (1947)), organic materials have been included in this enlarged database. For each soil entry, the fall-cone liquid limit was determined using the British Standard (BS) fall-cone method (i.e. using the 30°, 80 g cone with the liquid limit taken at $d = 20$ mm) (BSI (1990) or a predecessor standard) and the thread-rolling w_P result was reported. (BSI (2018a) now permits the use of a 60°, 60 g cone with the liquid limit taken at $d = 10$ mm.).

Figure 1 shows the database soils plotted on the standard plasticity chart, revealing that a large range of soil types is present in the database. Some high-loss-on-ignition (LOI) peats are included in the TCD database and in Vardanega *et al.* (2019), and when combined with the other data sources, a large range of soil plasticity values is present.

Regression analysis showed that a power-law relationship fitted to the data (Fig. 2) can find a fall-cone plasticity index, denoted in this paper as I_{Pc} (%), that matches the standard plasticity index, I_P (%), to within about 50% (see Fig. 3) (it is shown later that this apparently high potential error does not

Table 1. Database sources

Database	Source publications	n	Notes
Vardanega & Haigh (2014)	Sherwood & Ryley (1970)	20	UK, African and Turkish soils (soils referred to as 8, 15, 19, 20 and 25 not included)*
	Harison (1988)	7	Bandung clays (Indonesia)
	Feng (2000)	5	Taiwanese and Panamanian soils
	Zentar *et al.* (2009a)	3	Dunkirk sediments (tests F12 and F13 not included)*
	Zentar *et al.* (2009b)	2	Dunkirk sediments (some tests not included)*
	Kyambadde (2010)	52	Ugandan and UK soils (tests S32 and S34 not included as no thread rolling w_p values reported)
	Azadi & Monfared (2012)	2	Azerbaijani soils (only tests performed using British Standard fall-cone included)
	Haigh (2012)	3	UK soils
	Di Matteo (2012)	6	Italian (Paglia) alluvial soils
	Yin & Rui (2020)†	1	West Nile Delta marine sediment (Egypt)
TCD database	Author files	15	Glacial tills, Kilbeggan clay and Monasterevin silt-interlaminated clay, Ireland
	O'Kelly (2005)‡	5	Peats, marl, organic marl, Ireland
	O'Kelly (2006)‡	4	Thinly laminated silt and clayey-silt from Waterford and fine fibrous peat, Ireland
	O'Kelly (2008)‡	1	Residue from Ballymore Eustace water treatment plant (WTP), Ireland
	O'Kelly & Quille (2010)‡	2	Residue from Leixlip and Clareville WTPs, Ireland
	O'Kelly (2013)‡	1	Biosolids from Tullamore waste-water treatment plant, Ireland
	O'Kelly (2014a)	1	Residue from Ballymore Eustace WTP, Ireland
	O'Kelly (2014b)‡	1	Residue from Ballymore Eustace WTP, Ireland
	O'Kelly & Sivakumar (2014)‡	2	Clara and Derrybrien bog peats, Ireland
	O'Kelly (2015)‡	5	Glacial till, Ireland
	Sivakumar *et al.* (2015)‡	10	Canadian, Tennessee, Donegal, Belfast, Enniskillen, Ampthill, London and Oxford Clays, Belfast sleech and kaolin
Other publications	Campbell (1975)	24	Arable topsoils from south-east Scotland (data from both operators included in the analysis)
	Sampson & Netterberg (1985)	6	Southern African soils
	Vardanega *et al.* (2019)	16	Soils derived by removing fibres from peat materials sourced from southwest of England
	Sridharan *et al.* (1999)§	41	Indian soils ($\mathrm{FI_c}$ reported but not the individual fall-cone readings)

*Due to lack of or insufficient fall-cone readings in the plastic range.
†Originally cited in Vardanega & Haigh (2014) as 'Yin (2012) personal communication' as the paper had yet to be published.
‡Fall-cone liquid limit values and other geotechnical properties reported in original papers, but not the raw fall-cone test data (raw data stored in the original author's files).
§Sridharan *et al.* (1999) compared their database with data from Campbell (1975), Sampson & Netterberg (1985) and Sherwood & Ryley (1970), and they showed that the value of the coefficient in equation (4) did not change significantly.

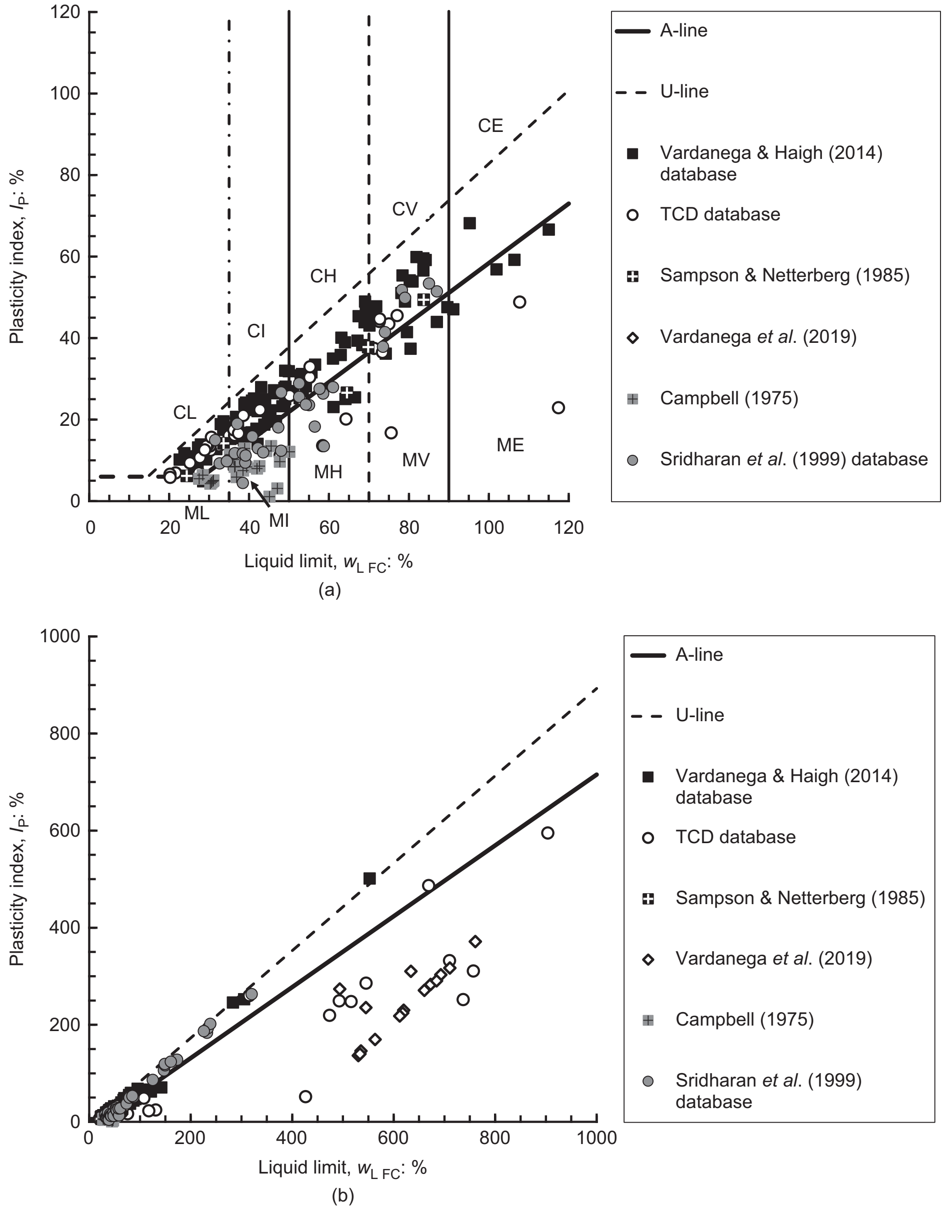


Fig. 1. Soils described in Table 1 plotted on the standard plasticity chart: (a) $w_{L\ FC}$ < 120%; (b) $w_{L\ FC}$ high range (plasticity chart design based on Casagrande (1947), Howard (1984) and BSI (1999))

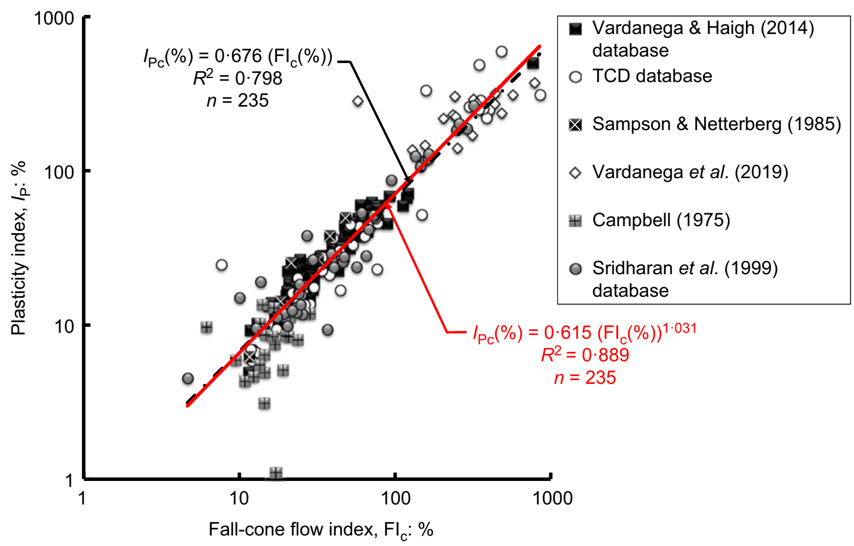


Fig. 2. Correlation of the flow index of Sridharan *et al.* (1999) with plasticity index

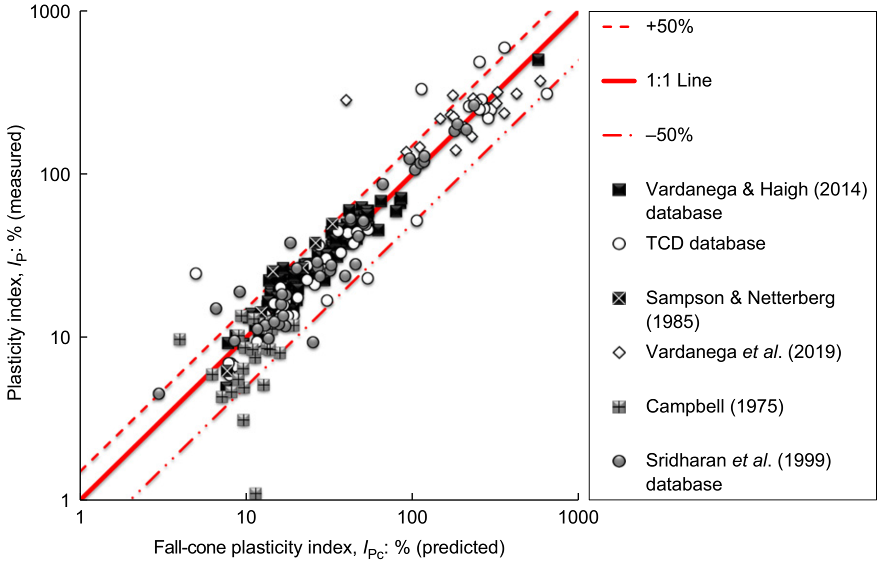
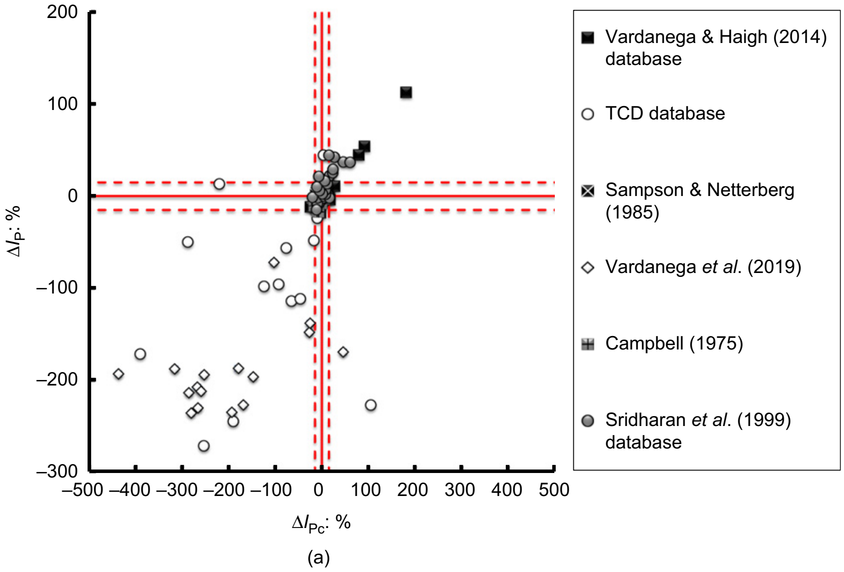


Fig. 3. Measured against predicted plot for equation (5) with ± 50% bounds shown



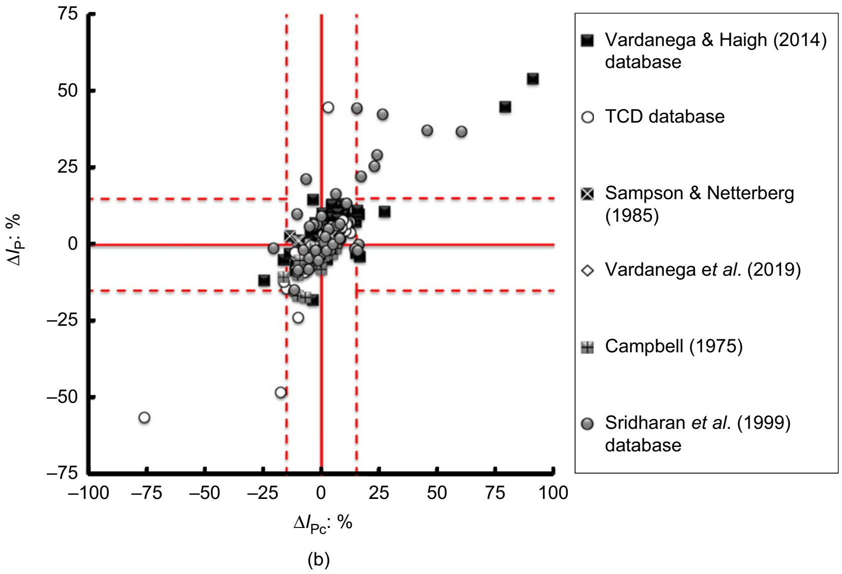


Fig. 4. Height above A-line (±15% bounds shown): soils in the lower left and upper right quadrants do not change their classification when equation (5) is used in lieu of the thread-rolling w_P data: (a) all database points shown; (b) zoomed plot for $-100 < \Delta I_{Pc}$ (%) < 100

prevent adequate classification of the soils in the database; however, equation (5) should not be used to predict the results of the thread-rolling test for w_P determinations)

$$I_{Pc}(\%) = 0{\cdot}615\,(\mathrm{FI_c}(\%))^{1{\cdot}031} \quad R^2 = 0{\cdot}89,\; n = 235 \quad \text{(valid up to } w_{L\,FC} \approx 800\%) \tag{5}$$

For comparison with equation (4) from Sridharan *et al.* (1999), the following linear fit to the Table 1 dataset is reported

$$I_{Pc}(\%) = 0.676\,(\mathrm{FI_c}(\%)) \quad R^2 = 0{\cdot}80,\; n = 235 \tag{6}$$

Based on its better goodness of fit, equation (5) is used in the subsequent analysis in this paper.

$\mathrm{FI_c}$ is the slope of a linear fit to fall-cone data plotted on semi-log axes (equation (3)) and as such its accuracy depends on the range of the distribution of water contents over which fall-cone data are available. Therefore, to ensure a good fit in the plastic range, soils were excluded from the analysis if insufficient fall-cone tests were reported for which cone penetration was less than 20 mm, as noted in Table 1.

Given that the liquid limit for the database is defined using the BS fall-cone method (i.e. $w_{L\,FC}$) and its interpretation is not changed in this analysis, it is clear that the soils' positioning can only shift vertically on the plasticity chart as a result of differences between the predicted cone plasticity index I_{Pc} (%) and standard plasticity index I_P To investigate the changes in position relative to the A-line, the following ΔI_P parameter, as defined in Wesley (2003) to indicate height above the A-line on the standard plasticity chart, is used

$$\Delta I_P(\%) = I_P(\%) - 0{\cdot}73\,[w_L\,(\%) - 20] \tag{7}$$

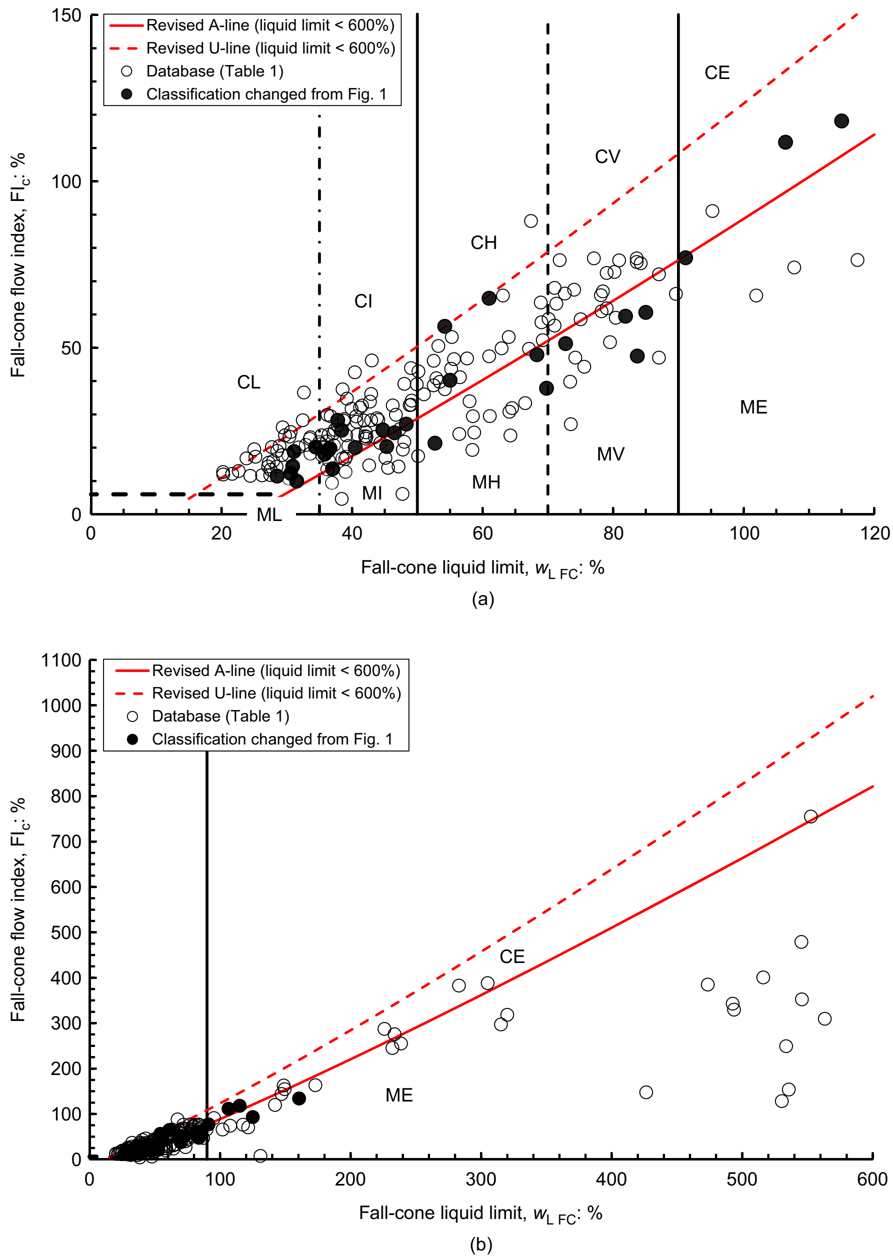


Fig. 5. New soil plasticity chart based on British Standard fall-cone flow index and liquid limit parameters: (a) chart for $w_{L\,FC} < 120\%$; (b) chart for $w_{L\,FC} < 600\%$. Note: data from Fig. 1 are shown on this plot to compare the classification systems, with those points indicated by solid black markers identifying soils that change classification category for implementation of the new plasticity chart. Equations (10) and (11) shown as revised A- and U-lines

Figure 4 shows ΔI_P (%) plotted against ΔI_{Pc} (%), the equivalent height above the A-line on the modified chart which is derived using equation (8) (note that the liquid limit used in both ΔI_P and ΔI_{Pc} calculations (i.e. Equations (7) and (8), respectively) was derived from the fall cone).

$$\Delta I_{Pc}(\%) = I_{Pc}(\%) - 0{\cdot}73\,[w_{L\ FC}(\%) - 20] \tag{8}$$

From this comparison, although some scatter exists about the trend, the soils which change classification (35/235 soils considered) are mostly ones that originally lay very close to the A-line. Sherwood (1970) reported on the basis of a large multi-laboratory testing programme that the thread-rolling w_P operator error when testing the same soil could be as great as 10–15%, a finding that was confirmed more recently by the results of Sivakumar *et al.* (2009, 2015). Although this error could be reduced by repeat testing and improved control of the testing process, the database values of plastic limit have not been subjected to this rigour and so must be assumed to have a possible 15% error. Any soil lying within 15% of the A-line in terms of its plasticity index must hence have the possibility of having been misclassified by the standard process. Examination of Fig. 4 shows that only 2/235 soils both change their classification (i.e. clay as opposed to silt) and fall outside the ± 15% bounds shown, indicating that for soil classification purposes equation (5) is an acceptable alternative to the determination of the conventional plasticity index, I_P. The strong correlation between the ΔI_P and ΔI_{Pc} values would be symptomatic of two systems with broadly similar results.

NEW CLASSIFICATION CHART

Before updating the A-line and U-line given by equations (1) and (2), respectively, it must be recalled that they were originally determined using Casagrande's method for liquid limit determination (i.e. the percussion-cup method). As the proposed classification chart is based purely on fall-cone testing, it is appropriate to incorporate correlations linking the Casagrande cup and fall-cone liquid limits for percussion-cup devices with appropriate base

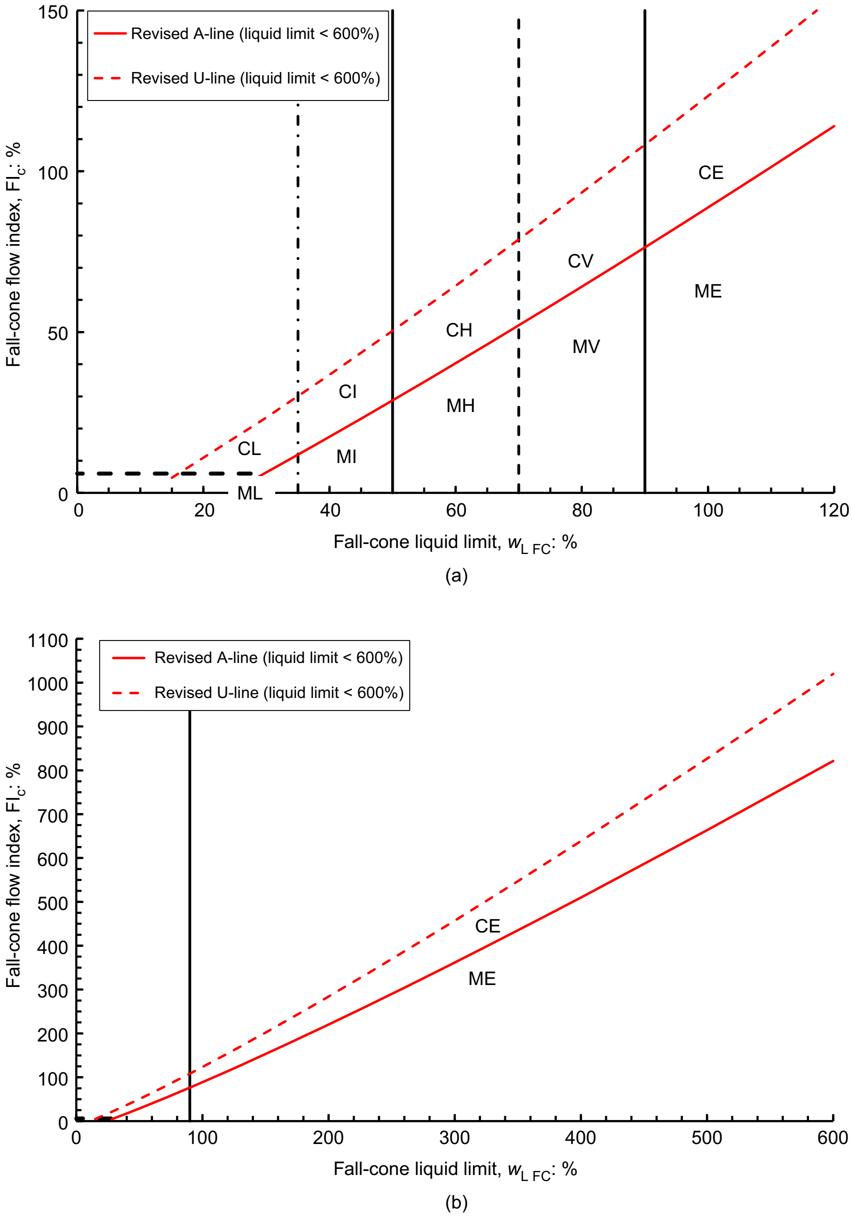


Fig. 6. New soil plasticity chart based on British Standard fall-cone flow index and liquid limit parameters: (a) chart for $w_{L\ FC}$ < 120%; (b) chart for $w_{L\ FC}$ < 600%. Equations (10) and (11) shown as revised A- and U-lines

hardness (Haigh, 2016); given that Di Matteo *et al.* (2016) showed that 'boundary materials' can be classified rather differently simply by switching from the Casagrande cup method to the fall-cone method for liquid limit determination.

O'Kelly *et al.* (2018, 2020) produced equation (9) linking the BS fall-cone liquid limit to that obtained for the ASTM percussion cup, considering w_L values of up to 600% (a similar range to that for equation (5)). It should be noted (as expected following the work of Haigh (2012)) that at high values of w_L there is substantial divergence in the liquid limit values obtained using the two methods.

$$w_{L\,FC} = 1{\cdot}90(w_{L\,ASTM})^{0{\cdot}85} \quad \text{(for } w_{L\,ASTM} \text{ (cup) values up to } \approx 600\%) \quad (R^2 = 0{\cdot}97,\ n = 199) \tag{9}$$

Using equations (5) and (9), the A-line and U-line equations (equations (1) and (2), respectively) can be redefined as equations (10) and (11).

Revised A-line

$$\mathrm{FI_c}(\%) = \left(\frac{0{\cdot}73}{0{\cdot}615}\left\{\left[\left(\frac{w_{L\,FC}}{1{\cdot}90}\right)^{(1/0{\cdot}85)}\right] - 20\right\}\right)^{(1/1{\cdot}031)} \approx \left[0{\cdot}558(w_{L\,FC}^{1{\cdot}176}) - 23{\cdot}74\right]^{0{\cdot}970} \tag{10}$$

where $w_{L\,FC}$ is expressed as a percentage.

Revised U-line

$$\mathrm{FI_c}(\%) = \left(\frac{0{\cdot}9}{0{\cdot}615}\left\{\left[\left(\frac{w_{L\,FC}}{1{\cdot}90}\right)^{(1/0{\cdot}85)}\right] - 8\right\}\right)^{(1/1{\cdot}031)} \approx \left[0{\cdot}688(w_{L\,FC}^{1{\cdot}176}) - 11{\cdot}71\right]^{0{\cdot}970} \tag{11}$$

where $w_{L\,FC}$ is expressed as a percentage.

Figure 5 shows a revised soil plasticity chart which makes use of the fall-cone flow index $\mathrm{FI_c}$ of Sridharan *et al.* (1999) (equation (3)) derived from data taken with the 30°, 80 g BS fall cone (BSI, 1990, 2018a). Plotted in this figure are the data from Fig. 1, with those data points that change soil classification category (see BSI, 1999, 2018b) indicated with solid black markers. (Note that the separation of the plasticity levels (e.g. CE, CV, etc.) as defined by BSI (1999) has not been changed, as BSI (1990, 2018a) already prefers the use of the fall-cone liquid limit.) Fig. 6 shows the revised plasticity charts, which are recommended for soil classification purposes without needing to use the conventional plastic limit (thread-rolling) test.

SUMMARY AND CONCLUSIONS

This paper has shown that fine-grained soil classification can be carried out to an acceptable degree of accuracy using only fall-cone data. If fall-cone data alone are used to do this, the operator should undertake such testing as far as practical across the plastic range to produce an accurate flow index ($\mathrm{FI_c}$) magnitude. In this paper, a new plasticity chart has been proposed on the basis of $\mathrm{FI_c}$ and fall-cone liquid limit (as determined using the 30°, 80 g cone with the liquid limit taken at $d = 20$ mm), both of which can be derived from a single fall-cone testing series. As two different soils can have the same fall-cone liquid limit and different computed values of $\mathrm{FI_c}$, these measures are arguably independent despite being obtained using data from the same test apparatus. If the water content indicating transition from the plastic state to the brittle state is needed, then the thread-rolling test must be retained. However, adopting the new chart, the thread-rolling plastic limit is no longer needed for soil classification purposes. This change removes the need for soil classification to rely on a test (thread rolling) that has high operator variability.

DATA AVAILABILITY STATEMENT

This study has not generated new experimental data.

NOTATION

d	cone penetration depth
F	flow index for Casagrande-cup test data
$\mathrm{FI_c}$	flow index for fall-cone test data
I_P	plasticity index based on thread-rolling plastic limit
I_{Pc}	fall-cone plasticity index inferred from flow index, $\mathrm{FI_c}$
n	number of data points used in developing a regression
R^2	coefficient of determination
r	correlation coefficient
w_L	liquid limit
$w_{L\,ASTM}$	liquid limit determined using ASTM Casagrande cup
$w_{L\,FC}$	liquid limit determined using the 30°, 80 g British Standard fall cone
w_P	plastic limit
ΔI_P	height above A-line on standard plasticity chart using I_P
ΔI_{Pc}	height above A-line on modified plasticity chart using I_{Pc}

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